Observation of NLIW in the South China Sea using PIES

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LONG-TERM GOALS

To study the mechanisms of generation, evolution and propagation of high frequency nonlinear internal waves [NLIW] in the vicinity and west of Luzon Strait in the South China Sea, making use of pressure equipped inverted echo sounders.

OBJECTIVES

Our objectives are (1) to observe the internal tide propagating west of Luzon Strait and its progressive evolution in shape and speed as it traverses the South China Sea under the influence of nonlinearity, non-hydrostatic effects, rotation, topography, currents and stratification, and (2) to interpret the results with the help of models that incorporate these effects.

APPROACH

Our approach involved deployment of three modified pressure equipped inverted echo-sounders [PIES], set up to transmit every 6s (see Fig.1). These instruments measure the return acoustic travel time from sea-floor to surface, which is modified by variations in the local stratification resulting from passage of internal waves. Knowledge of the background stratification is provided by CTD casts. Time series measurements of the acoustic travel time then provide a basis for inferring the first mode internal response. The observations are analyzed with 2-layer models: a weakly nonlinear model incorporating both generation and propagation, a fully nonlinear wave evolution model, and a model of the wave generation mechanism which is coupled to the fully nonlinear evolution model.

WORK COMPLETED

This project has now been completed and the planned goals have been met. During the past year the fully nonlinear model analysis of the data has been published (Li & Farmer, 2011). The approach has led to a preliminary investigation of internal tide generation in Luzon Strait using Hibya's (1986) model adapted for the two ridge topography of Luzon Strait. The output served as initial conditions for a wave evolution analysis and comparison with our observations using Helfrich's (2007) fully nonlinear model. These results are guiding the ongoing work under IWISE. In concluding this project we note that our work led to publication of an instrumentation and methods paper (Li et al., 2009). An initial analysis was conducted using Gerkema's (1996) 2-layer weakly weakly nonlinear model for

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generation and evolution of nonlinear internal waves (Farmer et al., 2009). Key individuals involved in the NLIWI project include PhD student Li Qiang (URI), Karl Helfrich (WHOI), Tim Duda (WHOI), Jae-Hun Park (URI); Erran Sousa (URI), instrument deployments and recovery; Steve Ramp (MBARI) led cruises essential to the field program. In addition a collaboration with Kevin Lamb (U. Waterloo) has resulted in publication (Lamb & Farmer, 2011) of a model analysis of instability growth in a nonlinear internal wave, motivated by prior observations.

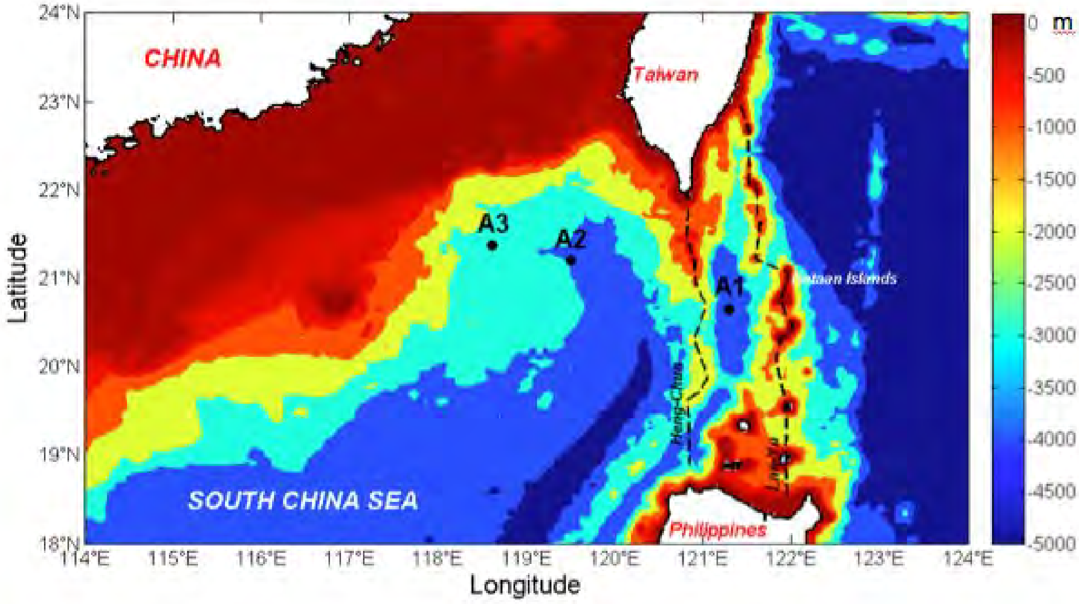

Fig 1: Chart of Luzon Strait showing deployments of inverted echo-sounders. A1 lies between the two ridges of Luzon Strait, A2 and A3 in the deep basin of the South China Sea.

RESULTS

1. Our model analysis of the inverted echo-sounder successfully described instrument performance across a wide range of wind and sea state conditions. Specifically the role of wind speed effects including the rough sea surface and ambient noise contributes to both travel time scatter and modest bias. An acoustical model reproduced results consistent with our observations. Inversion of the results to recover internal wave information was evaluated using the Dubreil-Jacotin-Long model and comparisons made with co-located temperature observations (courtesy of Steve Ramp (NPS/MBARI).

2. Ostrovky's (1978) weakly nonlinear, 2-layer rotational theory together with Boyd's (2005) nonlinear stability analysis provided an initial basis for interpreting results of field observations in the South China Sea. The theory evaluates wave evolution in the context of rotational dispersion and nonlinear steepening. The stability analysis illustrates the way in which nonlinearity tends to dominate for the semi-diurnal internal tide across the deep basin of the South China Sea, whereas rotation effectively inhibits steepening of the diurnal component. The theory appears to account for some key features of the observations such as the delayed appearance of high frequency nonlinear waves within Luzon Strait.

(3) Gerkema's (1996) weakly nonlinear 2-layer rotational model allows us to incorporate topography and internal tide generation. The model was implemented with two ridges in Luzon Strait and illustrates features of the generation and wave evolution, specifically the alternating pattern of high frequency nonlinear wave evolution that occurs during part of the fortnightly cycle. The model provides a convenient basis for evaluating the role of rotational dispersion. Rotational dispersion plays a major role in modifying the diurnal internal tide in the South China Sea, but has relatively less effect on the semi-diurnal tide.

(4) The fact that our measurements of the internal tide between the two ridges show little sign of nonlinear modification such as steepening or high frequency nonlinear wave development suggests that a linear theory may provide a reasonable representation of the generation process. Hibiya's (1986) two-layer model illustrates several features of the observed internal tides, including the consequence of a steady background flow, such as the Kuroshio intrusion. Doppler effects due to flow over the eastern ridge in Luzon could account for the modification of the internal tide so as to suppress nonlinear internal waves during strong intrusions. By including internal tidal generation at both ridges we find the results qualitatively consistent with observations at our easternmost mooring station A1 in the middle of Luzon strait.

(5) By combining Hibiya's generation model with Helfrich's (2007) fully nonlinear evolution model we were able to demonstrate the way in which different tidal forcing conditions accounted for the observed nonlinear internal waves in the deep basin. Fig. 2a shows a time series of the tidal current predicted across the eastern ridge in Luzon Strait, broken into the diurnal (red) and semi-diurnal (blue) components, each based upon the corresponding four greatest tidal constituents.

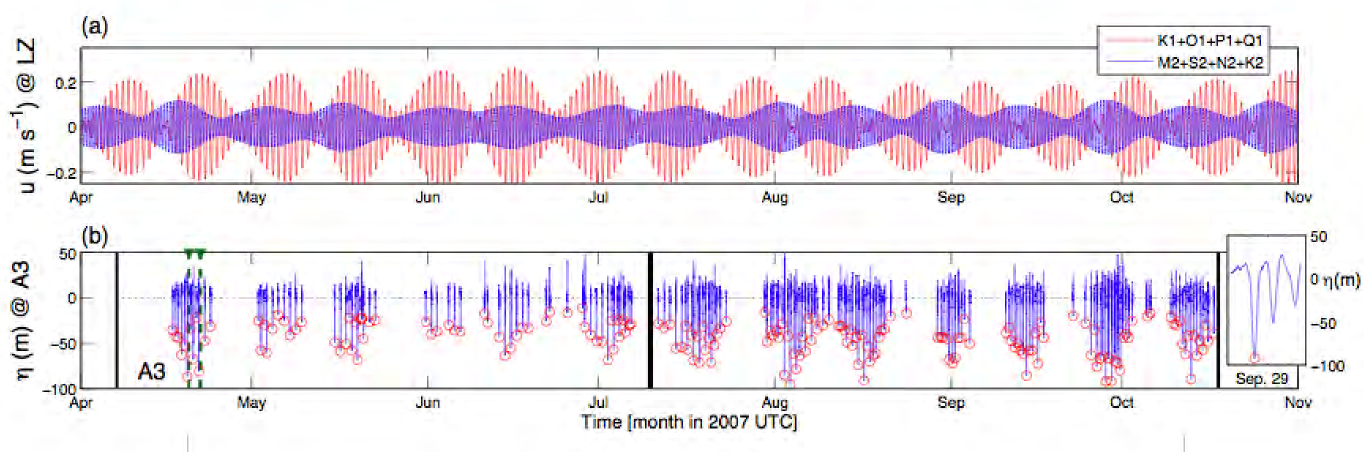

Fig. 2: (a) Semidiurnal (blue) and diurnal (red) predicted tidal component at Luzon Strait (122°E, 21°N). (b) Internal waves observed at A3. Vertical blue lines identify high frequency nonlinear internal waves detected at A (upper and lower bounds of the leading wave in a wave-train, illustrating intermittency of nonlinear internal waves and relationship to semidiurnal tidal forcing.

Fig. 2b shows the range (upper and lower bounds) of the leading wave at station A3, when a nonlinear internal wave packet is generated. Visual inspection and further analysis demonstrates that high frequency nonlinear internal waves tend to form during maximum semi-diurnal tides rather than diurnal tides. However, larger NLIW amplitudes tend to occur when the diurnal and semi-diurnal tides are in phase. This result is consistent with model calculations that combine internal wave generation with the fully nonlinear wave evolution model, as shown in Fig. 3. In this figure the top row shows three representative tidal current examples, semi-diurnal (3a), diurnal (3d) and mixed (3g). The second row shows the corresponding internal tide that is generated for each tidal current example, and the third row shows the predicted internal wave as it has evolved by station A3. Note that the semi-diurnal tide forms a high frequency nonlinear internal wave train, but the diurnal tide forms a large single wave. When the tides are mixed the response at A3 alternates between high frequency wave train and a single wave (3i). Despite the relative simplicity of the model, which is 2-dimensional and 2-layer, it is nevertheless able to reproduce and explain key features of the observations. Comparison of model predictions with observations for different tidal environments is shown in Figure 4.

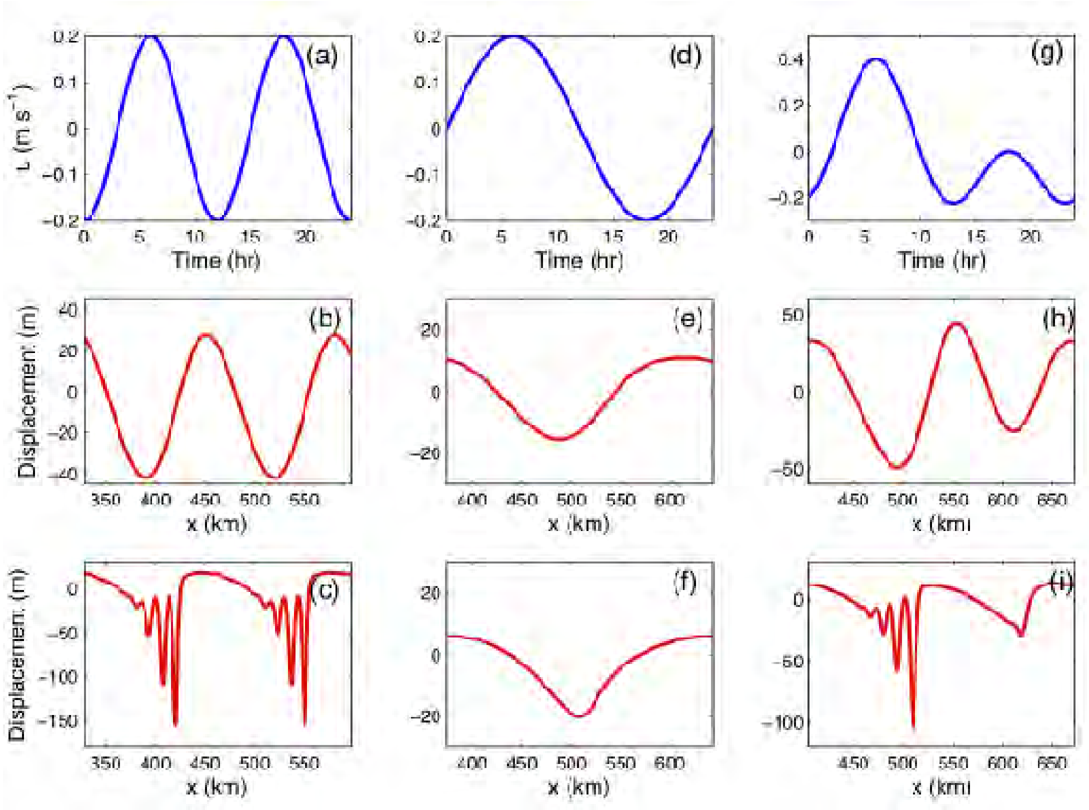

Fig. 3: Showing the effect of rotation on internal wave evolution in the fully nonlinear frame. Top row: idealised semi-diurnal, diurnal and mixed tidal current in Luzon Strait. Second row: corresponding internal tide. Third row: nonlinearly evolved internal wave at station A3.

(6) In related work on nonlinear internal waves with Kevin Lamb, instability and overturning in a wave observed off the Oregon coast was successfully modeled (Lamb & Farmer, 2011). Observations acquired in an earlier project off the Oregon coast motivated a numerical examination of conditions leading to instability. The observations also revealed the presence of anomalously light fluid in the center of the wave above the pycnocline. Simulations of a wave encountering a patch of light surface

water were used to model this effect. In the presence of a background current with near-surface shear, the simulated internal wave has a trapped surface core. As this wave encounters a patch of lighter surface water, the light surface water at first passes beneath the core, following which convective instabilities set in and the light fluid is entrained into the core. This results in the formation of overturning features, which exhibit some similarities with the observed overturns.

IMPACT/APPLICATIONS

Interpretation of the inverted echo-sounder observations using a sequence of models of graduated complexity provides a framework for identifying the mechanisms by which the well defined high frequency nonlinear internal wave trains are generated, contributing towards a predictive capability. The observational approach shows the utility of inverted echo-sounders for internal wave measurements. The model calculations illustrate the ability of simplified models to explain the physical basis of key aspects of the observations, thus providing a useful predictive ability. Our results to date, evaluated at a latitude of 21.3N, are consistent with generation of an internal tide over the eastern ridge, augmented at this latitude by interaction with generation over the western ridge. Rotational dispersion inhibits steepening of the diurnal internal tide while nonlinear effects dominate evolution of the semi-diurnal signal leading to formation of high frequency internal wave trains in the deep basin (Fig. 2) and accounting for the observed systematic variability in appearance of high frequency wave trains in the deep basin, including alternation in character of nonlinear internal waves during mixed tidal conditions (Fig. 3). Nonlinearity and rotational dispersion are the key factors in modifying the internal tide west of the strait and their inclusion in a 2-D 2-layer model is able to reproduce key aspects of the observed signal (Fig. 4). The coupled generation-evolution model provides a good prediction of nonlinear internal waves in the deep basin and should provide a reliable set of initial conditions for wave interaction with the slope and shelf region. These results are also proving helpful in planning further measurements under the IWISE program.

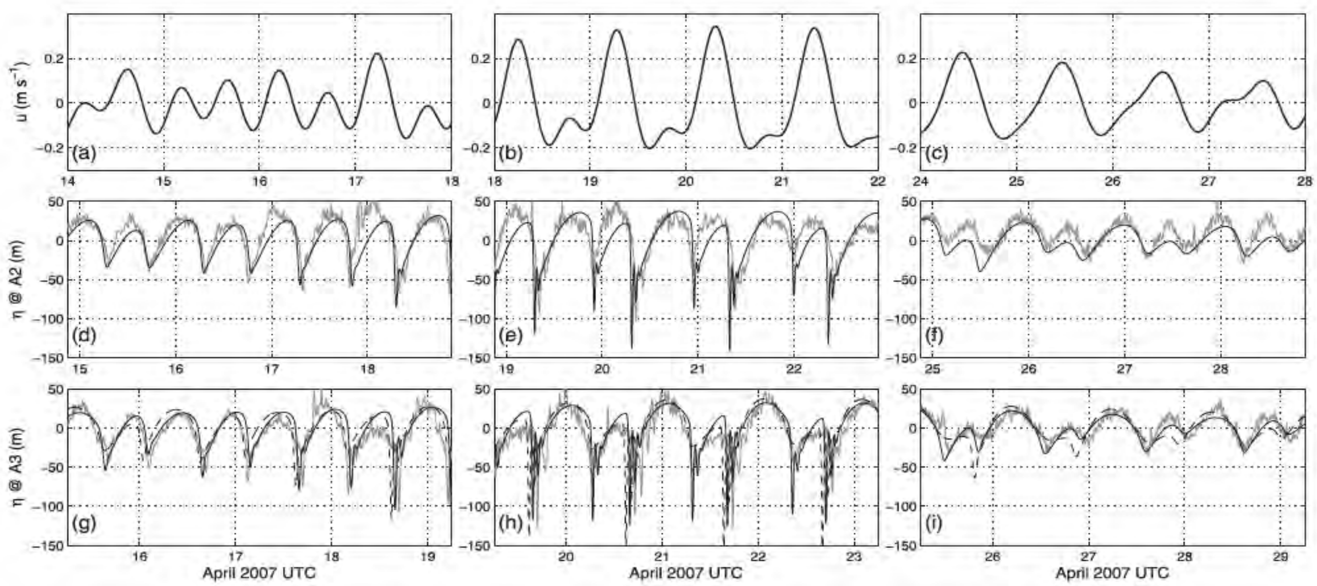

Fig 4: Top row shows predicted tidal current across the eastern ridge of Luzon Strait for three different representative examples of tidal conditions. Second and third rows showbothe observations (grey) and predictions (solid) at the two stations A2 and A3.

RELATED PROJECTS

ONR project – IWISE: Internal Waves in Straits

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